New Observational Frontiers in the Multiplicity of Young Stars

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It has now been known for over a decade that low-mass stars located in star-forming regions are very frequently members of binary and multiple systems, even more so than main sequence stars in the solar neighborhood. This high multiplicity rate has been interpreted as the consequence of the fragmentation of small molecular cores into a few seed objects that accrete to their final mass from the remaining material and dynamically evolve into stable multiple systems, possibly producing a few ejecta in the process. Analyzing the statistical properties of young multiple systems in a variety of environments therefore represents a powerful approach to place stringent constraints on star formation theories. In this contribution, we first review a number of recent results related to the multiplicity of T Tauri stars. We then present a series of studies focusing on the multiplicity and properties of optically-undetected, heavily embedded protostars. These objects are much younger than the previously studied pre-main sequence stars, and they therefore offer a closer look at the primordial population of multiple systems. In addition to these observational avenues, we present new results of a series of numerical simulations that attempt to reproduce the fragmentation of small molecular cores into multiple systems, and compare these results to the observations.

1. INTRODUCTION

The prevalence of binary and higher-order multiple systems is a long-established observational fact for field low-mass stars (*Duquennoy and Mayor*, 1991; *Fischer and Marcy*, 1992). For over a decade, it has been known that young pre-main sequence stars are also often found in multiple systems. The chapter by *Mathieu et al.* (2000) in the previous volume in this series has summarized various statistical surveys for visual multiple systems among T Tauri stars in star-forming regions as well as of zero-age main sequence stars in open clusters. These early multiplicity surveys have shown that multiple systems are ubiquitous among young stellar objects (YSOs) and further revealed an environment-dependent trend. The multiplicity rate in all stellar clusters, even those with the youngest ages such as the Orion Trapezium cluster, is in excellent agreement with that observed in main sequence field stars. On the other hand, the least dense T Tauri populations, like the Taurus-Auriga and Ophiuchus clouds, show a factor of $\sim$2 multiplicity excess, relative to field low-mass stars. However, it remained impossible to decide whether this behavior was the consequence of an intrinsic difference in the fragmentation process, or the result of dynamical disruptive interactions acting on timescales shorter than 1 Myr in stellar clusters (see *Patience and Duchêne*, 2001 for a review).

The purpose of this chapter is to review a variety of observational results concerning the multiplicity of young low-mass stars in order to update the view presented by *Mathieu et al.* (2000). In addition, we present some numerical results related to the fragmentation and subsequent evolution of low-mass prestellar cores. These models make predictions that can be readily tested with the observational results discussed here. Throughout this chapter, we focus on low-mass stellar objects with masses roughly ranging from 0.1 to $2M_{\odot}$. The multiplicity of young substellar objects is discussed in detail in the chapters by *Burgasser et al.* and *Luhman et al*, whereas the multiplicity of higher-mass objects is addressed in the chapter by *Beuther et al.* Other chapters in this volume present complementary insights on the subject: *Goodwin et al.* present more numerical results on the collapse and fragmentation of molecular cores, as well as on the dynamical evolution of small stellar aggregates; *Whitworth et al.*, *Ballesteros-Paredes et al.* and *Klein et al.*) discuss the collapse of larger-scale molecular cores; *Mathieu et al.* and *Monin et al.* focus on various proper-

ties (dynamical masses and disks properties, respectively) of known T Tauri binary stars.

2. AN UPDATE ON THE MULTIPLICITY OF YOUNG LOW-MASS STARS

As mentioned above, the first efforts to study young multiple systems were focused on determining the average number of wide companions per object in well-known pre-main sequence populations. Attempting to account for these multiplicity rates has led to various theories that involve the fragmentation of molecular cores and the subsequent dynamical evolution of aggregates of stars embedded in gaseous clouds. So far, the observed multiplicity rate of T Tauri populations alone has not proved entirely conclusive, and since the review by *Mathieu et al.* (2000), the focus of statistical studies of young multiple systems has shifted to other areas. Before probing much younger, still embedded multiple systems (Section 3), we review here a number of studies on T Tauri multiple systems that go beyond the surveys that were conducted in the 1990s.

2.1 Multiplicity In Young Nearby Associations

The clear dichotomy between high- and low-multiplicity star-forming regions has usually been considered evidence of an environment-dependent star formation scenario. However, since most stars form in stellar clusters, one could also consider that the rare molecular clouds that host too many companions are exceptions for yet undetermined reasons. Over the last decade, several groups of a few tens of stars with ages typically between ∼10 and 50 Myr have been identified in the Sun's vicinity based on their common three-dimensional motion and youth indicators (*Zuckerman and Song*, 2004). Most members of these associations are low-mass pre-main sequence stars. Therefore, these co-moving groups represent additional, nearby populations of young stars whose multiplicity could be expected to resemble that of the Taurus-Auriga population given their low stellar densities.

Soon after their discovery, systematic searches for visual companions were conducted in some of these groups in order to complement the previous surveys. For instance, *Chauvin et al.* (2002, 2003) and *Brandeker et al.* (2003) conducted surveys for visual companions in the TW Hya, Tucana-Horologium and MBM 12 groups; we include MBM 12 in this discussion despite the continuing debate regarding its distance (∼65 pc according to *Hearty et al.*, 2000, revised upwards to ~ 275 pc by *Luhman*, 2001). In their review of all known nearby associations, *Zuckerman and Song* (2004) marked those systems that were discovered to be multiple in these surveys or during pointed observations of individual objects. The average multiplicity rate in these associations range from 20% to over 60% but the small sample sizes preclude clear conclusions on any individual association. Averaging all associations listed in *Zuckerman and Song*'s review, and adding the MBM 12 surveys from *Chauvin et al.* (2002) and *Brandeker et al.* (2003), the average number of visual companions per member is 38.2±3.6%. Because of the range of distances to the stars involved in this survey, it is difficult to compare this to previous surveys of T Tauri stars, which were surveyed over a more homogeneous separation range. Nonetheless, the observed multiplicity rate in nearby young associations appears to be high, possibly as high as in Taurus-like populations. Future dedicated studies sampling a uniform separation range will help reinforce this conclusion.

2.2 Multiplicity Of The Lowest Mass T Tauri Stars

Most of the T Tauri multiplicity surveys summarized in *Mathieu et al* (2000) were focusing on objects with masses in the range 0.5–2$M_\odot$, essentially because of the limited sensitivity of high-angular resolution devices at that time. Multiplicity surveys conducted in recent years have, therefore, focused primarily on the multiplicity rate of the lowest mass T Tauri stars in known star-forming regions in order to determine the mass-dependency of the properties of multiple systems.

We first focus on systematic surveys for multiplicity among low-mass (0.1–0.5$M_\odot$) T Tauri stars. *White et al.* (in prep.) have obtained high angular resolution datasets on ~ 50 such objects in Taurus-Auriga that represent a nice comparison sample to the early surveys of *Ghez et al* (1993) and *Leinart et al.* (1993), for instance. They find that even low-mass T Tauri stars have a high multiplicity rate, although with a decreasing trend towards the lowest stellar masses. In addition, they find that multiple systems in which the primary has a mass $M_A \lesssim 0.4 M_\odot$ are confined to mass ratios higher than $M_B/M_A \sim 0.6$, and very rarely have projected separations larger than ~ 200 AU despite sensitive searches. Apart from the overall multiplicity excess among T Tauri stars, these trends are in line with the results of multiplicity surveys among lower mass main sequence field stars (*Marchal et al.*, 2003; *Halbwachs et al.*, 2003). These various mass-dependencies must be explained by models of fragmentation and early evolution of multiple systems.

Extending this approach to and beyond the substellar limit, *Bouy et al.* (2003) in the Pleiades and *Kraus et al.* (2005) in Upper Scorpius found that the trends for lower metalicity, tighter, and preferentially equal-mass systems are amplified in the brown dwarf regime, although the exact multiplicity frequency of young brown dwarfs is still under debate. Pre-main sequence brown dwarfs are discussed in more detail elsewhere in this volume (see chapters by *Luhman et al.* and *Burgasser et al.*).

2.3 Dynamical Masses Of Binary T Tauri Systems

The masses of T Tauri stars are usually determined through their location in the HR diagram in comparison to pre-main sequence evolutionary models. However, there is a long-standing debate on the validity domain of these models, which all include some, but not all, of the key physical

ingredients (e.g., *Baraffe et al.*, 2002). Empirical mass determinations for T Tauri stars have been attempted for many years, largely through the study of binary and multiple systems. A thorough analysis of the confrontation of current evolutionary models with empirical mass determinations of T Tauri stars has recently been presented by *Hillenbrand and White* (2004).

There are only a handful of known pre-main sequence eclipsing binaries (*Mathieu et al.*, 2000; *Covino et al.*, 2000, 2004; *Stassun et al.*, 2004), but fortunately optical/near-infrared follow-up studies of known, tight T Tauri binary systems can be used to estimate dynamical masses for non-embedded YSOs. This was first done through statistical means by observing small transverse motion of a number of binary systems, and assuming random orientation of the orbits (*Ghez et al.*, 1995; *Woitas et al.*, 2001). This led to the conclusion that the average total system mass for T Tauri multiple systems is about $1.7M_{\odot}$. This will be compared to dynamical masses of embedded multiple systems in Section 3.4.

In recent years, dynamical masses were determined for individual systems for which a substantial time coverage of their short orbital period could be achieved, and therefore a Keplerian orbit could be adjusted to the data (*Steffen et al.*, 2001; *Tamazian et al.*, 2002; *Duchêne et al.*, 2003; *Konopacky et al.*, 2006). Mass estimates range from 0.7 to 3.7 $M_{\odot}$ and are generally in agreement with model predictions. Significant uncertainties due to the limited orbital coverage and poor distance estimates are still left, but within a few years, substantial progress could be achieved. When this is done, it will be possible to discriminate between evolutionary models. For more details, we refer the reader to the review by *Mathieu et al.* in this volume.

2.4 Spectroscopic T Tauri Binaries

Due to the distance to most star-forming regions, visual binaries are usually detected if their separation exceeds 5–10 AU. However, for solar-type main sequence field stars, roughly a third of all companions have tighter separations (*Duquennoy and Mayor*, 1991), and cannot be spatially resolved even with current high-angular resolution devices. These tight systems are particularly interesting, as their formation mechanism may differ dramatically from that of wider systems: indeed, fragmentation of prestellar cores occurs on much larger linear scales than the sub-AU separation of spectroscopic binaries. On the other hand, it appears that neither fission (*Tohline*, 2002) nor the orbital decay of wider pairs induced by accretion or dynamical interaction within unstable multiple systems (*Bate et al.*, 2002) is able to produce the observed large population of systems with orbital periods of a few days to a few months. One must therefore try to detect spectroscopic binaries among T Tauri stars, which is no easy task when considering their strong activity, including the frequent veiling and additional line emission induced by accretion onto, and magnetic activity in the vicinity of, the central object.

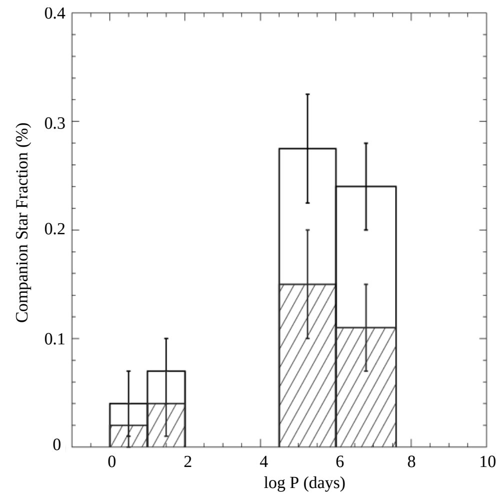

Fig. 1.— Orbital period distribution for T Tauri stars in several southern hemisphere star-forming regions (open histogram) compared to that of solar-type field stars (hatched histogram, from *Duquennoy and Mayor*, 1991); figure from *Melo* (2003). Note the non-significant excess of spectroscopic binaries.

First estimates of the frequency of T Tauri spectroscopic binaries were available since *Mathieu* (1994), but larger samples of objects have been spectroscopically monitored since then. Most noticeably, *Melo* (2003) has surveyed 59 T Tauri stars in four nearby star-forming regions during three campaigns over 2 years. He found 4 new double-lined spectroscopic binaries but could not determine their orbits due to limited time coverage. Within the interval $1^d \leq P_{orb} \leq 100^d$, the proportion of companions is on the order of a few percent. Once incompleteness corrections are taken into account, *Melo* finds almost twice as many companions as among field stars, however statistical uncertainties are large enough that this is not significant (see Fig. 1). While there could be as strong a multiplicity excess among short-period spectroscopic systems as there is for visual companions, it will not be possible to demonstrate it before much larger samples are monitored.

2.5 High-Order T Tauri Multiple Systems

As soon as the first multiplicity surveys were conducted among T Tauri stars, a few high-order multiple systems were identified, all triples and quadruples. T Tau, the eponymous low-mass pre-main sequence star, is itself a triple system (*Koresko*, 2000). The number of high-order multiple systems was too limited to pursue any statistical analysis of their frequency and properties at the time of the review by *Mathieu et al.* (2000). Among field solar-type stars, the frequency of high-order multiples is currently being revised from 10 times to 4 times lower than that of binary systems as high-angular resolution techniques and large surveys begin to expose the closer and wider companions (*Duquennoy and Mayor*, 1991; *Tokovinin and Smekhov*, 2002). Overall, high-order multiple systems may

appear to be of limited numerical strength, but their dynamical importance may be much higher. Estimating the frequency of these high-order systems may therefore turn out to be a more stringent constraint on fragmentation models than the average number of companions per star, irrespective of the system's number of components.

A first survey dedicated to the search for triple systems was conducted by *Koresko* (2002) in Ophiuchus, where he focused on already known binaries. Among 14 targets, he found 2 clear cases of triple systems and 5 more may also be triples, suggesting a high frequency of high-order multiples. More recently, *Correia et al.* (in prep.) targeted 55 known binaries (from the list of *Reipurth and Zinnecker*, 1993) located in various star-forming regions. They identified 15 triple and quadruple systems, i.e. a ratio of high-order multiples to binaries on order 4, similar to recent findings of *Tokovinin and Smekhov* (2002) for main sequence systems. However, it must be emphasized that the imaging surveys of *Koresko* and *Correia et al.* are only sensitive to companions wider than ~ 10 AU, so that the actual number of triple and quadruple systems may be much higher. Interestingly, *Melo* (2003) suggested that short-period, spectroscopic T Tauri systems have a tendency to host more visual companions that single stars. This result was recently confirmed by *Sterzik et al.* (2005), suggesting that the formation of sub-AU spectroscopic systems may be related to the presence of a third component on a stable outer orbit. For instance, *Kiseleva et al.* (1998) suggested that the combination of Kozai cycles and tidal friction within triple systems with high relative inclination could result in the shrinkage of the inner orbit down to periods of only a few days. While the actual frequency of high-order multiples among T Tauri stars is not yet firmly established, it is likely to place stringent constraints on star formation models.

Among the important properties of triple and higher-order multiple systems, the relative orientation of the inner and outer orbits can play an important role in the dynamical evolution of the systems, and may also provide insight on their formation mechanism. Among field triple systems, *Sterzik & Tokovinin* (2002) have found a "moderate" alignment of the inner and outer orbits' angular momentum vectors. Unfortunately, there are almost no T Tauri multiple systems for which a similar study can be performed at this point, mostly because of the long orbital periods associated with visual binaries at the distance of the closest star-forming regions. In the unique case of the young hierarchical system V 773 Tau, however, *Duchêne et al.* (2003) have argued that the inner 51 day orbital period is almost coplanar with the outer 46 yr orbital period, although the existing dataset is insufficient to solve all ambiguities in the orbital solution. In coming years, the increasing number of astrometric orbital solutions for binary young stellar objects, along with the capacity of long-baseline interferometers to spatially resolve known spectroscopic systems, will enable the study of the relative inclination of orbits within pre-main sequence triple systems.

3. EMBEDDED MULTIPLE PROTOSTARS

As summarized in the previous section, a high multiplicity rate is already established 1 Myr into the evolution of low-mass stars, as demonstrated by the many observations of populations of T Tauri stars. However, with these observations only, the observed dichotomy between young clusters and loose associations cannot be unambiguously explained with a single mechanism: different pre-collapse conditions and/or a differential dynamical evolution could be involved. Numerical analysis has shown that close encounters within dense clusters can substantially decrease the frequency of wide companions in less than 1 Myr (e.g., *Kroupa*, 1995), and that non-hierarchical systems decay to stable configurations through few-body interactions in less than a hundred crossing times, i.e., in 0.1 Myr or even less (e.g., *Anosova*, 1986; *Sterzik & Durisen*, 1998). It is therefore critical to conduct multiplicity studies in the youngest possible stellar populations in order to determine the "initial conditions" of the evolution of multiple systems. This is why the observational effort in this field has shifted in recent years towards the study of the multiplicity of even younger systems, namely embedded protostellar objects. The existence of extremely young (Class 0) multiple systems (e.g., *Wootten*, 1989; *Loinard*, 2002; *Chandler et al.*, 2005) shows that the formation of multiples most probably occurs very shortly after the apparition of the initial protostellar seeds. Class 0 and Class I sources represent objects whose age is believed to be on the order of a few $\times\ 10^4$ yr and a few $\times\ 10^5$ yr, respectively. While they may already be too old to be considered pristine from the point of view of dynamical evolution, these objects provide an opportunity to probe an intermediate stage of the star formation process, where some evolution has already taken place but, hopefully, is not yet over. Furthermore, it is possible that the youngest (Class 0) protostars have suffered only very little evolution. In this section, we focus on such embedded multiple systems in order to assert some of their basic properties, and how they compare to more evolved T Tauri multiple systems.

3.1 A Combination Of Observational Approaches

Already at the time of *Protostars and Planets IV*, a few embedded multiple systems were known (see, e.g., the discussion of L1551 IRS5 in *Mathieu et al.*, 2000). However, the first statistical surveys of such objects have only been conducted in the last few years with the advent of a newer generation of instruments. Because they are still enshrouded in their dusty cocoons, the youngest protostars are not detectable at visible wavelengths. They are often dim even in the near- and mid-infrared, and emit most of their luminosity at far-infrared and sub-millimeter wavelengths, where the angular resolution currently available remains limited. Fortunately, high angular resolution techniques are now available in the near-infrared, mid-infrared, and radio domains.

The most embedded, Class 0 protostars are often associated with relatively bright and compact radio emission. Indeed, they frequently power supersonic jets that generate free–free emission detectable at radio wavelengths (*Rodríguez*, 1997), they are surrounded by accretion disks whose thermal dust emission is sometimes still detectable in the centimeter regime (*Loinard et al.*, 2002; *Rodríguez et al.*, 1998, 2005a), and they often have active magnetospheres (*Dulk*, 1985; *Feigelson and Montmerle*, 1999; *Berger et al.*, 2001; *Güdel*, 2002). The former two mechanisms produce emission on linear scales of tens to hundreds of astronomical units, whereas the non-thermal emission related to active magnetospheres is usually thought to result from the interaction of mildly relativistic electrons with the strong magnetic fields (a few kGauss) which are often present at the surface of young, low-mass stars (e.g., *Valenti and Johns-Krull*, 2004; *Symington et al.*, 2005). This process, therefore, produces emission on very small scales, typically a few stellar radii. Interferometric radio observations (7 mm $\lesssim \lambda \lesssim$ 6 cm) can supply images of YSOs with such high angular resolution and excellent astrometric quality: NRAO's *Very Large Array* (VLA) and *Very Long Baseline Array* (VLBA) connected interferometers provide typical angular resolution of $0\farcs1$ and $0\farcs001$ in combination with astrometric accuracies of $0\farcs01$ and $0\farcs0001$, respectively. The combination of these two assets makes it possible with radio interferometry to identify tight binaries among those protostars which emit centimeter radio waves, and study their orbital motions.

Class I protostars, which are more evolved and less deeply embedded, are strong mid-infrared emitters. The 10 μm radiation from each component does not originate from the star itself, but from a "photosphere" of surrounding dust heated to several hundred degrees. According to the radiative transfer model of *Chick and Cassen* (1997), the 10 μm photosphere is located about 1 AU from a low-mass protostar. In the mid-infrared regime, direct imaging on the newest generation of instruments on 6-10m telescopes provides deep, diffraction-limited ($\lesssim 0\farcs3$) images that are extremely sensitive to protostars, and whose spatial resolution largely surpasses current space capabilities. At such a spatial resolution, the individual components of Class I sources should be point sources in the mid-infrared, and easy to disentangle from one another.

As far as ground-based observations are concerned, the near-infrared regime currently offers the best combination of spatial resolution (diffraction limit on the order of $0\farcs05$ for 8-10m telescopes), sensitivity, and field of view. The spectral energy distribution (SED) of Class I protostars extends into the near-infrared and, as in the mid-infrared, the light emitted by these objects comes from a very small photosphere that remains unresolved. Near-infrared observations have therefore become one of the most powerful approaches to study the multiplicity of Class I protostars. Observations in this regime not only allow the discovery of very tight companions, but also provide a probe of the evolutionary state of individual components: the latter is directly related to the spectral index of YSOs in the near- to mid-infrared regime (*Lada*, 1987).

Taking advantage of these complementary techniques, we will now discuss several recent results concerning young embedded multiple systems: their average multiplicity rate, their evolutionary status, and high-precision astrometric follow-up studies (orbital motions, possible dynamical decays).

3.2 The Multiplicity Of Low-Mass Embedded Protostars

3.2.1. Radio Imaging Surveys. One of the first systematic surveys for multiplicity of embedded YSOs was conducted by *Looney et al.* (2000) with the BIMA interferometer at 2.7 mm. Although companions as wide as 15000 AU could be identified in this survey, one must be cautious that such wide systems may not be physically bound. Considering a 2000 AU upper limit for projected separation, a value frequently used for other multiplicity surveys, and focusing on the Class 0 and Class I sources in their sample, 3 out of the 16 independent targets actually are binaries and none is of higher multiplicity. Still, this is quite a high multiplicity rate considering the relatively large lower limit on projected separation (60-140 AU depending on the molecular cloud): it is somewhat higher than the rate observed for solar-like field stars. Furthermore, it must be emphasized that millimeter observations have a limited sensitivity to YSOs in multiple systems with separations of a few hundred AUs because their disks are much reduced as a result of internal dynamics (*Osterloh and Beckwith*, 1995; *Jensen et al.*, 1994). Overall, the limited size of the sample studied by *Looney et al.* (2000) warrants statistically robust conclusions, and the main outcome of this pioneering work was to confirm the prevalence of multiple systems on a wide range of spatial scales among the youngest embedded protostars.

In parallel to this study, *Reipurth* (2000) also emphasized that low-mass embedded objects are frequently binary or multiple. In his study of 14 sources driving giant Herbig-Haro flows (mostly Class 0 and Class I sources), based on a variety of high-angular resolution datasets, he concluded that they had an observed multiplicity rate between 80 and 90%, and that more than 50% of them were higher order multiples. He further suggested that strong outflows could be the consequence of accretion outburst occurring during the dynamical decay of unstable high-order multiple systems. If this statement is correct, the extremely high multiplicity rate may be overestimated due to a selection bias. In posterior VLA continuum studies on a larger sample of mostly Class I sources and with a uniform observing strategy, *Reipurth et al.* (2002, 2004) found a binary frequency of 33% in the separation range from 0.5$''$ to 12$''$ for a sample of 21 embedded objects located between 140 and 800pc from the Sun. Within the uncertainties, this binary frequency is comparable to the observed binary frequency among T Tauri stars in a similar separation range. Among this new sample, 4 out of 7 objects that drive giant molec-

ular flows were found to have companions, a marginally higher rate that is not sufficient for any conclusions to be reached on the multiplicity-outflow connection.

3.2.2. Near-Infrared Imaging Surveys. Independent systematic surveys of the multiplicity of embedded protostars were later conducted at near-infrared wavelengths (1–4 μm) on samples of several tens of Class I and "flat spectrum" embedded sources. A first series of surveys (*Haisch et al.*, 2002, 2004; *Duchêne et al.*, 2004) were conducted using wide-field near-infrared cameras, which permitted seeing-limited observations. Sources in the Perseus, Taurus-Auriga, Chamaeleon, Serpens and ρ Ophiuchi molecular clouds were targeted. To derive a robust multiplicity rate, we define here a "restricted" companion star fraction by focusing on the 300–1400 AU projected separation range, for which all targets have been observed, and by retaining only those companions which satisfy $\Delta K \leq 4$ magnitude, following *Haisch et al.* (2004). Merging all surveys into one large sample, there are 119 targets, for which 19 companions are identified within these limits. This corresponds to a multiplicity rate of 16.0±3.4%, with all clouds presenting entirely consistent rates. The multiplicity rate found for Class I sources in Taurus and ρ Ophiuchi is in excellent agreement with those obtained for T Tauri stars in the same star-forming regions, and is about twice as high as that observed for late-type field dwarfs (see Fig. 2). A few systems present very large near-infrared flux ratios (up to $\Delta K \sim 6$ magnitudes); if the physical nature of these pairs is confirmed, these companions could be candidate proto-brown dwarfs, whose frequency should then be compared to the (very rare) occurrence of wide star-brown dwarf systems among field stars. Alternatively, these systems could be understood as the association of two objects whose evolutionary states are different, with the fainter star still being much more deeply embedded. Only subsequent mid-infrared imaging and/or high resolution spectroscopy will help disentangle these two options.

To study in more detail the frequency and properties of multiple systems, higher spatial resolution observations are required. Indeed, such observations enable the discovery of many more companions and, in particular, of a number of stable hierarchical triple and higher-order multiple systems. *Duchêne et al.* (in prep.) have recently conducted an adaptive optics imaging survey of 44 Class I protostars located in the Taurus-Auriga, ρ Ophiuchi, Serpens, and Orion (L 1641) molecular clouds. The diffraction-limited images they obtained on the 8m-VLT allowed companions as close as $0\farcs1$ (< 20 AU in the closest clouds) to be resolved, providing an order of magnitude improvement in spatial resolution from previous surveys, and identifying a dozen subarcsecond companions that were not known previously. Combining these observations with direct images of the same sources from previous surveys, and concentrating on the 36–1400 AU separation range, there are a total of 23 companions fulfilling the $\Delta K \leq 4$ magnitude criteria, representing a total multiplicity rate of 52.2±7.5%. Within current statistical uncertainties, observations are consistent with the hypothesis that Class I multiple systems have essentially the same properties in all clouds. Among this high-angular resolution sample, 6 systems are triple, including 5 in which the ratio of projected separations is high enough to consider that they are hierarchically stable. No higher-order system was identified in this survey. The observed proportion of triple systems ($\sim 14\%$) is comparable to that observed among T Tauri stars (see Section 2.5), and may be higher than the proportion of such systems among field stars.

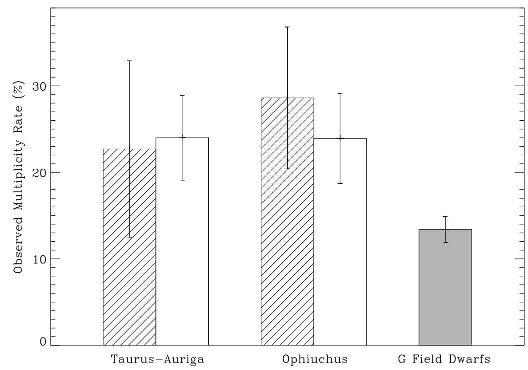

Fig. 2.— Observed multiplicity rates in the projected separation range 110–1400 AU for Class I protostars (hatched histograms) and T Tauri stars (open histogram) in the Taurus-Auriga and Ophiuchus molecular clouds; adapted from *Duchêne et al.* (2004). The multiplicity rate for field solar-type stars from *Duquennoy and Mayor* (1991) is shown for reference.

3.2.3. Spectroscopic Surveys. The radio and near-infrared surveys conducted so far have been able to identify companions with separations of several tens to hundreds of AUs. However, as mentioned already, many companions to low-mass field stars are on much tighter orbits. While VLBA observations already provide an opportunity to resolve some tight spectroscopic binary systems if they are strong radio emitters (see Section 3.4), it remains difficult to conduct a systematic analysis of the frequency of spectroscopic binaries among embedded protostars with imaging techniques. An alternative approach is to obtain high resolution spectra of protostars to identify spectroscopic binaries. Despite the difficulty induced by the partially opaque envelope that surrounds these objects, this spectroscopic effort is now ongoing, both at visible and near-infrared wavelengths (see the chapter by *Greene et al.* in this volume). Using single-epoch radial velocity measurements for a sample of 31 Class I and flat-spectrum protostars in several star-forming regions, *Covey et al.* (2006) found 4 objects whose radial velocities significantly depart from that of the surrounding local gas velocity. None of the objects were found to be double-line spectroscopic binaries, and their discrepant radial velocities either indicate that they have been ejected after an unstable multi-body interaction, or that they are

single-line spectroscopic binaries. Long-term monitoring of these objects will reveal their true nature. At any rate, this preliminary study shows that systematic searches for spectroscopic binaries among embedded protostars are now feasible. We can therefore hope to rapidly complement existing imaging surveys to almost completely cover the entire range of orbital periods from a few days up to separations of several thousand AU. Comparing such surveys to the known properties of field stars would be important to determine whether the tightest systems actually form through a different mechanism than wide pairs.

3.2.4. Implications For Star Formation Scenarios. Overall, these surveys for multiplicity among embedded protostars consistently support the general scenario in which all star-forming regions produce a very high fraction of binary and higher-order multiple systems, at least as high as that observed among T Tauri stars in the most binary-rich regions like Taurus-Auriga. While there is marginal evidence for a decrease in multiplicity rate between the most and least embedded protostellar sources (*Duchêne et al.*, 2004), no significant evolution of the multiple system population has been found in regions like Taurus or Ophiuchus within the $\lesssim 1$ Myr timescale during which protostars evolve into optically bright T Tauri stars. The absence of mini-clusters of 5 or more sources within $\sim\ 2000$ AU implies that if cores frequently fragment into many independent seeds, they must decay into unbound stable configurations within a very short timescale, on the order of $\sim\ 10^5$ yrs at most. The relatively low number of protostars found to be single in the surveys presented here ($\lesssim\ 50$%), however, suggests that cores can rarely result in the formation of unstable quadruple or higher order multiples, supporting the point of view recently presented by *Goodwin and Kroupa* (2005). This and other star formation models are further discussed in Section 4.2.

One of the most intriguing results that arises from these surveys is the finding that there seems to be no influence of environmental conditions on the multiplicity of embedded protostars, as opposed to what is observed for T Tauri multiple systems. Namely, Class I protostars in Orion (in the L1641 cloud) show as high a multiplicity excess over field stars as all categories of YSOs in the Taurus and ρ Ophiuchi clouds. This seems to favor a scenario in which the end result of core fragmentation is independent of large scale physical conditions, but rather is sensitive only to small-scale physics which may well be very similar in all molecular clouds. As already discussed by *Kroupa et al.* (1999), dynamical disruptions among an initial population of binary systems can account for the deficit of wide binaries observed for optically bright YSOs in dense clusters, even though the population of "primordial multiple systems" has universal properties. Based on the present observations, we may conclude that such disruptive encounters, which represent a distinct process from the internal decay of unstable multiple systems, is likely to occur in the densest clusters on a timescale of $\sim$ few $\times \sim 10^5$ yrs.

3.3 Evolutionary Status Within Multiple Protostars

Haisch et al. (2006) have recently obtained new mid-infrared observations of 64 Class I and flat-spectrum objects in the Perseus, Taurus, Chamaeleon I and II, ρ Ophiuchi, and Serpens dark clouds. They detected 45/48 (94%) of the single sources, 16/16 (100%) of the primary components, and 12/16 (75%) of the secondary/triple components of the binary/multiple objects surveyed. The 10 μm fluxes, in conjunction with $JHKL$ photometry from *Haisch et al.* (2002, 2004), were used to construct SEDs for the individual binary/multiple components. Each source was classified using the least squares fit to the slope of its SED between 2.2 and 10 μm in order to quantify their nature. The classification scheme of *Greene et al.* (1994) has been adopted in our analysis as it is believed to correspond well to the physical stages of evolution of YSOs (*e.g. André and Montmerle*, 1994). A Class I object is one in which the central YSO has attained essentially its entire initial main-sequence mass, but is still surrounded by a remnant infalling envelope and an accretion disk. Flat-spectrum YSOs are characterized by spectra that are strongly veiled by continuum emission from hot, circumstellar dust. Class II sources are surrounded by accretion disks, while Class III YSOs have remnant, or absent, accretion disks. Thus, the progression from the very red Class I YSO $\rightarrow$ flat spectrum $\rightarrow$ Class II $\rightarrow$ Class III has been frequently interpreted as representing an evolutionary sequence, even though *Reipurth* (2000) has suggested that more violent transitions from the embedded to the optically-bright stages could occur when components are ejected from unstable multiple systems.

3.3.1. Nature Of "Mixed" Systems. While the composite SEDs for all YSOs in the *Haisch et al.* (2006) study are either Class I or flat-spectrum, the individual source components sometimes display Class II, or in one case Class III, spectral indices. The SED classes of the primary and secondary components are frequently different. For example, a Class I object may be found to be paired with a flat-spectrum source, or a flat-spectrum source paired with a Class II YSO. Such behavior is not consistent with what one typically finds for T Tauri stars, where the companion of a classical T Tauri star also tends to be a classical T Tauri star (*Prato and Simon*, 1997; *Duchêne et al.*, 1999), although mixed pairings have been previously observed among Class II YSOs (e.g., *Ressler and Barsony* 2001). Indeed, there appears to be a higher proportion of mixed Class I/Flat-Spectrum systems (67%, *Haisch et al.*, 2006) than of mixed CTTS/WTTS systems (25%, *Hartigan and Kenyon*, 2003; *Prato et al.*, 2003; *McCabe et al.*, 2006; see review by *Monin et al.* in this volume).

While several of the Class I/Flat-Spectrum binary components lie in regions of a $JHKL$ color-color diagram which are not consistent with their SED classes, they all lie in their expected locations in a KLN color-color diagram. In fact, in this diagram, one can see a clear progression from the very red Class I YSO $\rightarrow$ flat spectrum $\rightarrow$ Class II

(*Haisch et al.*, 2006). Taken together with the above discussion, this demonstrates the fact that while in most cases the SED class reflects the evolutionary state of the YSO, there may be instances in which the SED class does not yield the correct evolutionary state. The rigorously correct way to determine an objects' evolutionary state is to obtain multi-wavelength imaging data for each source and quantitatively compare these data to models produced using 3D radiative transfer codes (*Whitney et al.*, 2003).

Visual extinctions, A_v, have been determined for all binary/multiple components, except the Class I sources, for which accurate dereddened colors cannot be derived using infrared color-color diagrams. In general, the individual binary/multiple components suffer very similar extinctions, A_v, suggesting that most of the line-of-sight material is either foreground to the molecular cloud or circumbinary in nature.

3.3.2. Notes On Selected Objects. Among the various mid-infrared surveys to date, several sources deserve specific mention. A detailed study of WL 20, the only non-hierarchical triple system among embedded protostars, by *Ressler and Barsony* (2001) and *Barsony et al.* (2002) has suggested that disk interaction has resulted in enhanced accretion onto one component of this system, WL 20S. This tidally-induced disk disturbance could explain the Class I SED of this object, although it is probably coeval, at an age of several million years, with its Class II companions. On the other hand, the recent high-angular resolution images obtained in the near-infrared by *Duchêne et al.* (in prep) as part of their multiplicity survey revealed a completely unexpected morphology that does not seem to be consistent with a ~ 1 AU opaque envelope photosphere. Rather, it seems like WL 20 S is a normal T Tauri system whose circumstellar material has such a geometry that only scattered light reaches the observer shortwards of $\sim 5\mu$m, emphasizing the need for high angular resolution images to determine the actual nature of an embedded YSO.

IRS 43 (also known as YLW 15) in Ophiuchus was found to be a binary VLA source with $0\rlap{.}''6$ separation (*Girart et al.*, 2000). IRS 43 is also part of a wide-binary system with GY 263 (*Allen et al.*, 2002). *Haisch et al.* (2002) find IRS 43 to be multiple at 10 μm but single in the near-infrared. The brighter mid-infrared source in IRS 43 corresponds to VLA 2 and the heavily-veiled, Class I near-infrared source. VLA 1 is an embedded protostar, undetected in the near-infrared, and possibly in the Class 0 to Class I transition and powering a Herbig-Haro outflow. Its mid-infrared emission appears slightly resolved with a diameter of ∼16 AU, possibly tracing circumstellar material from both the envelope and the disk (*Girart et al.*, 2004). Both VLA/mid-infrared sources associated with IRS 43 are embedded in extended, faint near-infrared nebulosity imaged with HST/NICMOS (*Allen et al.*, 2002). Strikingly, the near- to mid-infrared properties of YLW 15 suggest that VLA 1 is a more embedded YSO, or alternatively, less luminous than VLA 2, whereas orbital proper motions of this binary system by *Curiel et al.* (2003) indicate that VLA 1 is more massive than VLA 2. This is apparently against the expected evolutionary scenario, in which one expects that the more massive YSO in a binary system is the more evolved and more luminous YSO.

Another source, ISO-Cha I 97 in Chamaeleon I, was detected as a single star in the near-infrared; however, mid-infrared observations have revealed that this source is in fact binary (*Haisch et al.*, 2006). The K-band sensitivity limit from *Haisch et al.* (2004), combined with its 10 μm flux, yields an extremely steep lower limit to the spectral index that places ISO-Cha I 97 in a class of YSO that has heretofore been rarely known. Three such objects have been recently reported, the Class 0 object Cep E mm (*Noriega-Crespo et al.*, 2004), source X_E in R CrA (*Hamaguchi et al.*, 2005), and source L1448 IRS 3 A (*Ciardi et al.*, 2003; *Tsujimoto et al.*, 2005). Further very steep spectrum YSOs are expected to be discovered with the Spitzer Space Telescope.

Spatially resolved mid-infrared spectroscopy of the Class I/flat-spectrum protostellar binary system, SVS 20 in the Serpens cloud core, has been recently obtained by *Ciardi et al.* (2005). SVS 20 S, the more luminous of the two sources, exhibits a mid-infrared emission spectrum peaking near 11.3 μm, while SVS 20 N exhibits a shallow amorphous silicate absorption spectrum with a peak optical depth of $\tau \sim 0.3$. After removal of the line-of-sight extinction by the molecular common envelope, the "protostar-only" spectra are found to be dominated by strong amorphous olivine emission peaking near 10 μm. There is also evidence for emission from crystalline forsterite and enstatite associated with both SVS 20 S and SVS 20 N. The presence of crystalline silicate in such a young binary system indicates that the grain processing found in more evolved Herbig Ae/Be and T Tauri pre-main-sequence stars likely begins at a relatively young evolutionary stage, while mass accretion is still ongoing. A third component to the system was found by *Duchêne et al.* (in prep.), making the analysis of the system even more complex.

Finally, *Meeus et al.* (2003) have presented mid-infrared spectroscopy of three T Tauri stars in the young Chamaeleon I dark cloud, CR Cha, Glass I, and VW Cha, in which the silicate emission band at 9.7 μm is prominent. This emission was modeled with a mixture of amorphous olivine grains of different size, crystalline silicates, and silica. The fractional mass of these various components was found to change widely from star to star. While the spectrum of CR Cha is dominated by small amorphous silicates, in VW Cha (and in a lesser degree in Glass I), there is clear evidence of a large amount of processed dust in the form of crystalline silicates and large amorphous grains. Interestingly, the two objects with an "evolved" dust population are associated with a tight companion, leading to the intriguing speculation that multiplicity may accelerate dust processing in cirucmstellar disks.

3.4 High-Accuracy Astrometry Of Embedded Multiples

As pointed out in Section 3.1, VLA and VLBA observations can provide a view of embedded protostars with an unsurpassed resolution and astrometric accuracy. This allows a number of studies that are impossible to conduct with shorter wavelength observations. We summarize here some recent results that take full advantage of VLA and VLBA capabilities to study embedded multiple systems.

3.4.1. Orbital Motion Within Embedded Multiple Systems. For a very limited subset of tight radio binaries associated with low-luminosity Class 0 and Class I deeply embedded sources, orbital motions have now been detected by comparing images taken at several epochs. It is very important to determine the system masses in order to constrain the time evolution of the central sources, and, for instance, to determine the fate of the material located in the circumstellar envelopes of Class I sources. Comparable estimates are already available for T Tauri stars (see Section 2.3).

Due to slightly poorer spatial resolution of VLA observations compared to the highest angular resolution near-infrared datasets, the embedded multiple systems for which orbital motion was detected typically have orbital periods of hundreds of years. Therefore, the multi-epoch observations to date only cover a small fraction of the orbit, and the exact orbital parameters cannot be derived. However, a reasonable estimate of the mass of the system can still be obtained assuming circular orbits, if the inclination can be guessed from independent means. The four sources where this could be achieved are IRAS 16293–2422 (*Loinard*, 2002; *Chandler et al.*, 2005) and YLW 15 (*Curiel et al.*, 2003) in ρ Ophiuchi, and L 1527 (*Loinard et al.*, 2002) and L 1551 (*Rodríguez et al.*, 2003) in Taurus-Auriga. The mass estimates are respectively: 2.8$\pm$0.7$M_{\odot}$; 1.7$\pm$0.8$M_{\odot}$, 1.0$\pm$0.5$M_{\odot}$, and 1.2$\pm$0.5$M_{\odot}$.

The mean value is therefore 1.7 $\pm$ 0.7 $M_{\odot}$, confirming that these low-luminosity, deeply embedded protostars are most likely the precursors of solar-type stars. Noticeably, this average mass is not significantly lower than that derived for T Tauri binary systems. Although small number statistics and selection biases preclude definitive conclusions at this stage, this seems to imply that the mass of the remnant envelopes in these systems are already significantly lower than the stellar seeds themselves; this is expected for Class I sources but may be more surprising for Class 0 sources. Future astrometric follow-up studies on these and other embedded tight binary systems will help clarify this issue.

3.4.2. Spectroscopic Systems Resolved With Interferometry. Most radio observations of embedded protostars have been conducted with the VLA. As mentioned above, the VLBA offers an angular resolution and an astrometric precision two orders of magnitude better than the VLA, but can detect YSOs that emit bright and compact non-thermal radio emission. Although all protostars probably do generate non-thermal radiation at some level, those that are currently easily detectable represent only a limited sample. Recently, Loinard and coworkers have started to monitor 10 protostars in the Taurus and ρ Ophiuchi star-forming regions that are known to be non-thermal radio sources. Interestingly, at least 2 of these systems were found to be multiple with separations of only a few times $0\farcs001$, or a few tenths of an AU at the distance of these molecular clouds. The clearest case is that of V773 Tau which was previously known to be a spectroscopic binary (*Welty*, 1995), and had been found to be a double in previous VLBI observations (*Phillips et al.*, 1996). While V773 Tau is a T Tauri system, more embedded systems are among the sample studied in this survey and, if they are found to have a tight companion, they would represent the earliest stage at which spectroscopic binaries can actually be spatially resolved. In parallel to this VLBA approach, near- and/or mid-infrared long baseline interferometers (such as Keck or VLTI) could resolve these systems in the near future, allowing for powerful infrared-to-radio analysis. In any case, these very tight systems clearly have a much shorter period ($\lesssim$1yr) than the embedded multiple systems resolved so far, so one should be able to accurately measure their masses in a comparatively shorter time.

3.4.3. Hints Of Disruption? With high-angular resolution and high astrometric accuracy, following the relative motion within multiple systems may reveal departures from bound Keplerian orbits. In particular, the possibility of studying the internal dynamics of unstable multiple systems, if some can be found, is extremely appealing. A special case of this decay is the violent disruption of a triple system into an ejected single star and a stable binary system. Only radio observations with the VLA combine high resolution and astrometric accuracy with a relatively long time baseline. It is therefore not a surprise that the first two claims of possible disruption of young multiple systems have come from such observations.

Using multi-epoch archival VLA observations of the triple system T Tauri over almost 20 years, *Loinard et al.* (2003) have found that the trajectory of one of its components could not be easily explained in terms of a stable Keplerian orbit. Follow-up near-infrared observations have cast doubt upon this conclusion as the orbit of the putative ejected component has been seen to slow down and curve as if it were on a Keplerian orbit (*Furlan et al.*, 2003; *Tamazian*, 2004; *Beck et al.*, 2004). However, no satisfying orbit has been fit simultaneously to all infrared and radio observations, and the exact correspondence of the detected sources at both wavelengths is still under debate (*Johnston et al.*, 2004, 2005; *Loinard et al.*, 2005). Following the system in both wavelength regimes for a few more years should yield a final conclusion to this issue.

More recently, *Rodríguez et al.* (2005b) and *Gómez et al.* (2006) have shown that three of the four compact radio sources around the Orion Becklin-Neugebauer/Kleinmann-Low region are moving away from a common point of origin, where they must have been located about 500 years ago (Fig. 3). These three radio sources are apparently associated

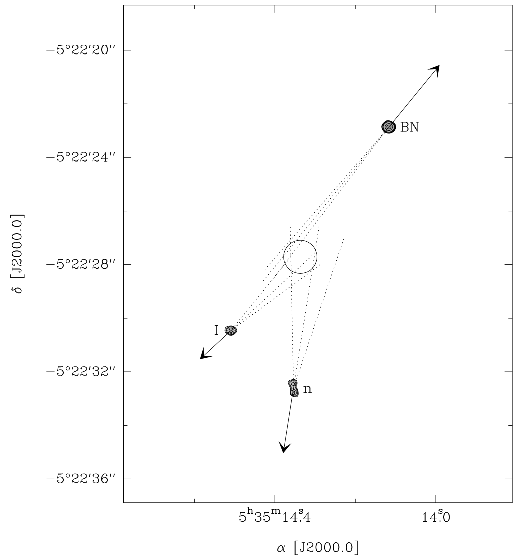

Fig. 3.— Proper motion of three radio sources in the Becklin-Neugebauer/Kleinman-Low region, from *Gómez et al.* (2006). They all trace back to the same point in space and time, 500 years ago.

with relatively massive young stars (M $> 8\ M_\odot$), suggesting that a massive multiple system disintegrated around that time. Although a different point of origin for the Becklin-Neugebauer object and an eightfold longer timescale has been advocated by *Tan* (2004), there is little doubt that this system was formed as an unstable multiple system, and has very recently experienced a dynamical ejection event.

These two cases remain open to discussion, and are insufficient to assess the exact relevance of few-body encounters to the final rates of multiplicity in stellar systems. However, they demonstrate the potential of radio interferometry to tackle this important issue, and should be pursued in upcoming years.

4. CORE FRAGMENTATION AND EARLY DYNAMICAL EVOLUTION OF MULTIPLE SYSTEMS

In this section, we review some of the most recent numerical simulations that aim at following the processes of collapse and fragmentation of a prestellar core as well as the subsequent dynamical interactions within the multiple systems resulting from fragmentation. More specifically, we concentrate on three different models of star formation, namely those by Goodwin and collaborators (*Goodwin et al.*, 2004a,b), Sterzik and collaborators (*Sterzik and Durisen*, 1995, 1998; *Durisen et al.*, 2001; *Sterzik et al.*, 2003), and Delgado-Donate and collaborators (*Delgado-Donate et al.*, 2004a,b), with special emphasis on the latter two. A more detailed description of other simulations can be found in two other chapters in this volume (*Whitworth et al.* and *Goodwin et al.*).

4.1 A Brief Overview Of Current Simulations

For some time, numerical models with predictive power on the statistical properties of young stars (e.g. multiplicity fractions, mass ratio, semi-major axis distributions) had to rely on pure N-body integration of the break-up of small clusters of point masses (*Sterzik and Durisen*, 1995, 1998; *Durisen et al.*, 2001). The masses, location, and velocities of the stars had to be selected at the outset, and subsequently the orbital evolution was calculated. This approach to multiple star ‘formation’ has the advantage of being easy and fast to calculate, so that many realizations of the same initial conditions could be run. However, it completely neglects the modeling of gas fragmentation, collapse, and accretion, a highly demanding task from a computational point of view. Yet, gas is a fundamental ingredient of the star formation process, not only during the fragmentation and collapse stage, but also during the embedded phase of the life of a star. Gaseous material accumulates in the form of accretion disks around the protostars, and these disks can modify substantially both the orbital parameters of a protobinary (*Artymowicz and Lubow*, 1996; *Bate and Bonnell*, 1997; *Ochi et al.*, 2005) and the outcome of dynamical encounters with other cluster members (*McDonald and Clarke*, 1995). Furthermore, under adequate physical conditions, disks can fragment, and in doing so, produce a second generation of objects (*Gammie*, 2001; *Lodato and Rice*, 2005). Gas also acts on the large scale throughout the embedded phase of star formation by providing a substantial contribution to the gravitational potential of the system. In this manner, gas can affect the mass evolution and motion of both single and multiple stars, hence the binary pairing outcomes, through the action of gravitational drag (*Bonnell et al.*, 1997, 2003; *Delgado-Donate et al.*, 2003). Although they prioritize the N-body dynamics over the gas dynamical processes, the simulations by Stezik and collaborators provide useful constraints on what effects dynamical interactions alone can have on the star formation process. Interestingly, these calculations provide the best match to date to the mass dependence of the multiplicity fraction of stars, as is constrained by our present observational knowledge. They do so by means of a 2-step procedure (*Durisen et al.*, 2001), whereby the stellar masses are picked randomly from a stellar mass function, subject to the additional constraint that the total cluster mass equals a value also picked randomly from a cluster mass function. This way, they alleviate the usually steepening effect of the process known as dynamical biasing – i.e. the strong trend of the two most massive stars in a cluster to pair together – on the multiplicity-vs-primary mass curve, by having a significant number of clusters where the two most massive stars have both low masses. This major success of N-body models is unmatched by current gas dynamical calculations, which so far are just able to give a positive but too steep dependence of the multiplicity fraction on primary mass (see Section 4.2). This success should not mask an obvious caveat, however: it remains unclear at present how a cluster may break into subunits which fragment into stars with the appropriate mass spectrum set by the 2-step process.

Early star formation models that included the effect of gas did so to study the formation of binary stars from clouds subject to some kind of specific initial instability (see the reviews by *Sigalotti and Klapp*, 2001 and *Tohline*, 2002). These models have been of great importance, but a caveat remained: they produce a low number of objects in a more or less predictable fashion. Other models tried to take into account large numbers of stars embedded in a big gas cloud (*Bonnell et al.*, 2001), e.g. by utilizing point masses with the ability to accrete and interact with the gas and other stars ('sink particles'; *Bate et al.*, 1995), but once more, with positions and velocities selected at the outset. These models focused mostly on the study of the resulting initial mass function. The purely gas dynamical models had to be refined and taken to a larger scale, while the aim of point-masses-in-gas models had to shift to the study of the properties of multiple stars, if star formation models were to match the predictive power of N-body models. The earliest model to take such step was that by *Bate et al.* (2003), who applied more general 'turbulent' initial conditions to a relatively large (for theory standards) $50 M_\odot$ cloud and followed its fragmentation and collapse down to the opacity limit for fragmentation. For higher densities, pressure-supported objects were replaced by 'sink particles' and, thus, the simulation could be followed well beyond the formation of the first objects. This calculation showed the power of the combination of more realistic initial conditions and a refined numerical scheme blending gas with N-body dynamics and, beyond any doubt, it meant a great leap forward in star formation studies; but, obviously, it had some shortcomings too. Among them was the high computational expense involved, and the fact that the evolution of the cloud could not be followed for as long as it would be desirable in order to ensure the stability of most multiples. Thus, complementary calculations were necessary, and these were performed mainly by Delgado-Donate and collaborators and Goodwin and collaborators. The *Goodwin et al.* (2004a,b) and *Delgado-Donate et al.* (2004a,b) simulations model the fragmentation of small ($\approx 5 M_\odot$) molecular clouds subject to different degrees of internal turbulent motion. Their models basically differ in the resolution employed, and the different subsets of parameter space studied: most importantly for this review, *Goodwin et al.* study subsonic turbulence whereas *Delgado-Donate et al.* impose supersonic to hypersonic random velocity fields. Both sets of simulations address the solution of the fluid equations (Smoothed Particle Hydrodynamics, SPH) and the dynamic creation of point masses to replace collapsed gas fragments in a similar manner. In the *Delgado-Donate et al.* calculations, SPH simulations follow the gas-dominated stage during ≈ 0.5 Myr before switching to an N-body integration followed until the stability of most of the multiples could be guaranteed. Each set of initial conditions is run 10 to 20 times, varying only the spectrum of the turbulent velocity field imposed initially, in order to obtain statistically significant average properties.

Finally, some numericists focused on the largest scales, and tried to study the collapse and fragmentation of large clouds (100 to a few $1000 M_\odot$; *MacLow and Klessen*, 2004, *Padoan and Nordlund*, 2002). These models reproduce the filamentary structure observed in molecular clouds, and find that cores are not quasi-static structures, but rather grow in mass by accretion and merge hierarchically until a specific core mass function (resembling the initial mass function at the high mass end) is built. While these simulations provide an important step for our understanding of the collapse of entire molecular clouds, they have little, if any, predictive power regarding the properties of individual or multiple stars. We do not consider these simulations in this review, which focusses on testing models against some of the most constraining observational data available, the properties of multiple stars at the earliest stages. These simulations are discussed in other chapters to this volume (*Ballesteros-Paredes et al.*, *Klein et al.*).

4.2 Predictions And Comparisons With Observations

These numerical simulations make a number of predictions regarding the statistical properties of young multiple systems. Ideally, these predictions should be tested against the observational results summarized in *Mathieu et al.* (2000) and in previous sections of this chapter, for instance. However, because of the limited parameter space that has been explored to date, and the daunting task of including all relevant physical processes, such predictions may still be premature. In the following, we consider a few such predictions, focusing primarily on general trends rather than detailed quantitative predictions, and briefly mention some other models that could be relevant for the formation of multiple systems.

4.2.1. Triples And Higher-Order Multiples. The *Delgado-Donate et al.* simulations produce a wealth of multiple systems. The companion frequency (average number of companions per primary) at 0.5 Myr after the initiation of star formation is close to 100%, whereas the frequency of multiple systems (ratio of all binary and higher-order systems to all primaries) is $\approx 20\%$; in other words, for each binary/multiple system, there are 4 isolated single objects. Clearly, multiple star formation is a major channel for star formation in turbulent flows, as found also by *Bate et al.* (2003), *Bate* (2005) and *Goodwin et al.* (2004a,b), but in these simulations, high-order multiples are more frequent than binaries. The systems can adopt a variety of configurations, like binaries orbiting binaries or triples. Such exotic systems have been observed, and currently, the occurrence of high-order multiples among main sequence field stars is of order ~ 15–25% (e.g., *Tokovinin*, 2004). A similar proportion of multiple systems was found in both T Tauri and embedded protostars populations (see Section 2.5 and 3.2). The *Goodwin et al.* (2004b) calculations, characterized by a very low ratio of initial turbulent energy to thermal energy, produce a significantly lower number of stars per core, and match better the observed multiplicity fractions. This has led *Goodwin & Kroupa* (2005) to propose that the main

mode for star formation involves the break-up of a core into 2 to 3 stars, a larger number being a rare outcome. This is a revealing constraint on star formation theories although it does not settle the question of how this main mode of 2-to-3 fragments comes to be (low turbulence is a possibility but there may be others) and which multiplicity properties we should expect from it.

4.2.2. Multiplicity As A Function Of Age. *Delgado-Donate et al.* found that the companion frequency decreases during the first few Myr of N-body evolution, as many of the initial multiple systems are unstable. It must be noted that, although the canonical timescale for dynamical break-up of an unstable multiple is at most 10^5 yr, this timescale is significantly increased in these gas dynamical simulations because of two effects. First, numerous companions form on orbits with very large separations, up to orbital periods approaching the 10^5 yr timescale. Second, it is found in gas dynamical calculations that star formation always occurs in bursts, which repeat themselves with decreasing intensity for several cluster free-fall times, i.e. several $\times\ 10^5$ yr, adding new stars to already formed, and maybe already stable, multiples. While the former effect may be a somewhat artificial consequence of the selected initial conditions, the latter is very robust, and likely applies to most star formation scenarios.

The total companion frequency is seen to rapidly decay from $\approx 100\%$ to $\approx 30\%$. This internal decay affects mostly low-mass outliers, which are released in vast amounts to the field. It might be expected that in a real cluster the companionship would drop even further – or sooner – as star forming cores do not form in isolation but close to one another. Weakly bound outliers might have been stripped sooner by torques from other cluster members (see simulations by *Kroupa et al.*, 1999, for instance). The total frequency of binary and high-order multiples, on the other hand, varies little after the first few $\times\ 10^5$ yr. Thus, although a multiple system is still likely to evolve further towards its hierarchical stable configuration in longer timescales, the relative frequency of singles, binaries, triples, and so on, seems to be essentially established after a few $\times 10^5$ yr.

Based on these models, one may expect that the frequency of binary/high-order multiples among T Tauri stars, which are already a few Myr old, should be essentially the same as that of main sequence field stars. While this is true for young clusters, loose associations clearly show a higher companion frequency, in disagreement with this prediction. It must be emphasized that the simulations discussed here consider prestellar cores as isolated entities, whereas core-core interactions may play an important role in shaping the outcome of the star formation process. Nonetheless, to reconcile these simulations with the observations, one can argue that a large number of the single objects produced by the simulations are not included in the observed samples of T Tauri stars, either because they are of too low-mass or because they have already been expelled from the molecular cloud owing to their high ejection velocities (see below) and the shallow potential well of the cloud. Both explanations have their own weaknesses: on one hand, the ratio of stellar-mass objects to brown dwarfs is on order 4 in the Taurus molecular cloud (*Guieu et al.*, 2006) and low-mass stars are frequently members of binary and multiple systems (see Section 2.2), and on the other hand, the much younger embedded protostars – although they may already be too old to be compared with the simulations – do not appear to have a dramatically lower proportion of single stars (see Section 3.2).

4.2.3. Multiplicity As A Function Of Primary Mass. The *Delgado-Donate et al.* models find a positive dependence of the multiplicity fraction on primary mass (see Fig. 4), in qualitative agreement with observations. The low- and high- mass end of the distribution, however, do not match satisfactorily the observations; the dependence on mass is too steep. The models fail to produce as many low-mass binaries as observed because of their extremely low binding energy, making them prone to disruption in an environment dominated by dynamical interactions. Observationally, a binary fraction of at least 15% is seen among field brown dwarfs (e.g. *Bouy et al.*, 2003, *Martín et al.*, 2003), and values as high as $30-40\%$ have been suggested (*Maxted and Jeffries*, 2005; but see *Joergens*, 2006). Secondly, the high-mass end shows a paucity of singles. This is a common outcome of all 'turbulent' star formation simulations to date, and stems from the fact that the most massive members of the cluster are always in binaries and thus, the binary fraction at the high-mass end is close to 100%, whereas even in the Taurus-Auriga cloud, there are a number $\gtrsim 1 M_\odot$ T Tauri stars that have no known companion. Calculations by *Goodwin et al.* also find similar problems to fit the observed multiplicity dependence of primary mass. It is likely that by simulating the evolution of an ensemble of clouds with different initial masses, thus following the successful prescription of a 2-step procedure pioneered by *Durisen et al.* (2001), the problem would be lessened, but it is unclear at the moment – until parameter space is more widely investigated – whether it would solve it completely or not. The problem of the formation of a significant population of low-mass/brown dwarf binaries would remain, and it has been suggested that initial conditions less prone to fragmentation or resolution effects may provide a possible solution to this riddle (*Clarke and Delgado-Donate*, in prep.). As mentioned before, *Durisen et al.* (2001) and *Sterzik and Durisen* (2003) extensively discuss how a steep multiplicity vs mass correlation can be smoothed, and manage to do so by means of their 2-step mass selection.

4.2.4. Velocity Dispersion. The simulations show that single and binary stars attain comparable velocities in the range $1-10$ km s^{-1}, whereas higher-order multiples display lower velocity dispersions. This kinematic segregation as a function of N is the expected outcome of the break-up of unstable multiples, whereby the ejected objects (typically singles, or less often binaries) acquire large veloci-

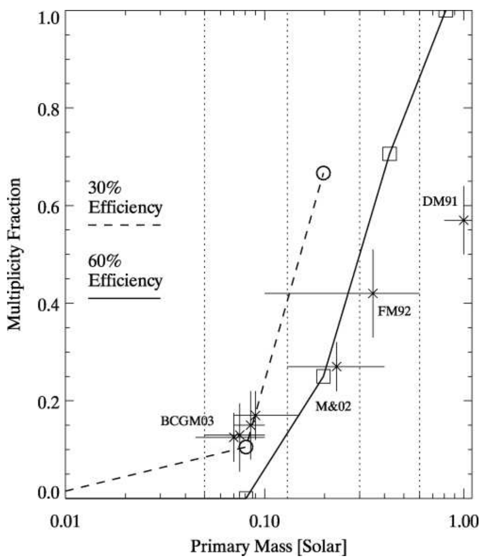

Fig. 4.— Predicted mass-dependence of the multiplicity rate (solid and dashed lines), from *Delgado-Donate et al.* (2004b). Observational datapoints are for field stars (*Duquennoy and Mayor*, 1991; *Fischer and Marcy*, 1992; *Marchal et al.*, 2003; *Bouy et al.*, 2003, in order or decreasing primary mass).

ties, whereas the remaining more massive multiple recoils with a lower speed. Among the singles and binaries, the peak of the velocity distribution is of order a few km s^{-1}, in the range of the cloud random velocities. A similar velocity distribution is produced by N-body models (*Sterzik and Durisen*, 2003) and models with lower levels of turbulence (*Goodwin et al.*, 2004a,b). Therefore, we would expect low-mass star-forming regions like Taurus, where a local kinematic segregation may survive against the influence of large scale dynamics, to display an overabundance of multiple systems in the densest regions, from where the high speed low-mass singles would have escaped. This prediction was made by *Delgado-Donate et al.* (2004b), and has been recently supported by the simulations of *Bate* (2005).

On the observational side, we note that the radial velocity outliers found by *Covey et al.* (2005) and discussed in Section 3.2 could be ejected protostars; only a long-term monitoring of their radial velocities will help determine their status. From another perspective, the most recent survey for low-mass Taurus members by *Guieu et al.* (2006), covering several times the area of previous surveys, has found that the fraction of brown dwarfs increases as one moves away from the densest cores, known before to be over-abundant in binaries. This could be an indication for an average larger speed for the lower-mass single objects, as predicted. A complete analysis of the spatial distribution of multiple systems in the Taurus cloud has not been performed yet, but would provide a crucial test of this prediction. Furthermore, there are some caveats on whether the census of low-mass stars in the extended area covered by *Guieu et al.* (2006) is complete. More observational work is still required to test this critical prediction of numerical simulations.

4.2.5. Other models. So far, we have reviewed models based on the pure N-body break-up of small clusters and models where an ‘initial’ turbulent velocity field is imposed to the cloud, so that its decay triggers the formation of structure until the Jeans instability takes over and produce multiple fragmentation. However, there are researchers that advocate a less dynamic view of star formation. This more quiescent star formation mode may be thought of as an extension of the *Shu et al.* (1987) paradigm of single star formation to multiple systems, whereby a core in quasi-static equilibrium collapses from the inside out in such a way that only a few independent fragments are formed. The statistical properties of multiple systems formed in this way are almost impossible to predict in the absence of a detailed physical framework for this “quiescent fragmentation”, but can be constrained *a posteriori*. To simultaneously match the high frequency of companions to low-mass stars and the paucity of quadruple and higher-order multiples among populations of T Tauri stars and embedded protostars, *Goodwin and Kroupa* (2005) have concluded that this star formation mode must produce primarily binary and triple systems. *Goodwin et al.*’s low turbulence simulations are the closest we have at the moment to a paradigm of not-so-dynamic star formation. Alternatively, *Sterzik et al.* (2003) also find that clusters with low N are a better match for current observations.

In addition, there exists the possibility that the numerical scheme used in most models reviewed in this section, i.e. SPH, may not perform entirely satisfactorily in some of the regimes modeled, especially when shear flows or voids are involved. There are alternatives to SPH, most of them based on adaptive mesh refinement techniques, that could offer a different view on the problem. Efforts by Padoan and collaborators go in that direction, as well as those by Klein and coworkers, but the complexity of the codes and the implementation of sink particles or their equivalent for grid codes, essential to follow star formation calculations beyond the formation of the first star, have proved a serious obstacle so far to produce simulations comparable in predictive power to the SPH ones. In addition, the role of feedback in the star formation process, e.g. through outflows, has never been included in such simulations, although it may be important. The effects of photoionizing feedback by massive stars have been preliminarily studied by *Dale et al.* (2005), who find that photoionization fronts may have both a positive and negative effect in star formation, by triggering fragmentation and collapse at the HII fronts, or disrupting incoming accretion flows respectively. These new developments are likely to shed light on some of the issues over which theory stays the furthest apart from observations.

5. CONCLUSIONS AND PERSPECTIVES

Binary and higher-order multiple systems represent the preferred outcome of the star formation process; studying

the statistical properties of these systems at various evolutionary stages, therefore, offers indirect constraints on the core fragmentation and on the subsequent dynamical interaction between gas and stars. While the (high) frequency of Myr-old T Tauri stars has now been long established, there has been tremendous progress in recent years: new populations of young stars have been surveyed, the frequency of high-order multiple and spectroscopic binaries among T Tauri stars is being accurately estimated, and embedded protostars have for the first time been surveyed for multiplicity. In the meantime, numerical simulations describing the fragmentation and dynamical evolution of prestellar cores towards fully-formed stars and multiple systems have made tremendous progress, and while they may not yet allow for a fine comparison of predictions with observations, they already predict significant trends that can be tested.

All these studies have provided important clues towards the star formation process, but a number of open questions remain to be solved. For instance, the apparent uniformity of the multiplicity rate of embedded protostars independent of environment is quite puzzling given the strong dependence to initial conditions of all numerical simulations of core fragmentation. Another surprising observational result is the existence of a fairly large proportion of low-binding energy multiple systems, which rarely survive the violent early star-and-gas dynamical evolution in numerical simulations of collapse and fragmentation. The absence of aggregates of more than 4–5 stars on scales of a couple thousand AUs is also surprising, as they seem to be ubiquitous in numerical simulations of the fragmentation and collapse of gas clouds. Could we be missing a number of young stars in molecular clouds, completely biasing our multiplicity surveys? If so, then we may wonder how useful the traditional Class 0–I–II–III evolutionary sequence really is: if stars usually form as part of unstable multiple systems, then many stars probably "jump" from one category to another over very short timescales, which could have dramatic consequences for their circumstellar environments. The existence of systems pairing stars of different evolutionary categories (including the "infrared companion" systems among T Tauri stars, which are not discussed in this chapter) could be footprints of this violent evolution, and would deserve increased attention in upcoming years.

To investigate these and many other issues described above, continuing both survey and follow-up efforts related to the multiplicity of young stars appears as a crucial endeavor for the future. While high-angular resolution ground-based infrared methods are bound to provide important new results, one must also remember that radio interferometric observations have the potential to complement infrared surveys in two major ways: first, by allowing the study of the youngest and most embedded protostars so far inaccessible to other techniques, and secondly, by providing images of extremely tight systems, which are so far only known to be binaries because of spectroscopy. They may also offer opportunities to examine the results of few-body disruption of initially non-hierarchical systems. In parallel to these observational efforts, more numerical simulations must be run to sample a wider parameter space than has been currently explored, and a general effort to include as many physical effects as possible must be undertaken in upcoming years to allow for direct comparisons of simulations with observations.

REFERENCES

Allen L. E., Myers P. C., Di Francesco J., Mathieu R., Chen H., and Young E. (2002) *Astrophys. J., 566*, 993-1004.

André P. and Montmerle T. (1994) *Astrophys. J., 420*, 837-862.

Anosova J. P. (1986) *Astrophys. and Space Science, 124*, 217-241.

Artymowicz P. and Lubow S. H. (1996) *Astrophys. J., 467*, L77-L80.

Baraffe I., Chabrier G., Allard F., and Hauschildt P. H. (2002) *Astron. Astrophys., 382*, 563-572.

Barsony M., Greene T. P., and Blake G. A. (2002) *Astrophys. J., 572*, L75-L78.

Bate M. R. (2005) *Mon. Not. Roy. Astron. Soc., 363*, 363-378 .

Bate M. R. and Bonnell I. A. (1997) *Mon. Not. Roy. Astron. Soc., 285*, 33-48.

Bate M. R., Bonnell I. A., and Price N. M. (1995) *Mon. Not. Roy. Astron. Soc., 277*, 362-376.

Bate M. R., Bonnell I. A., and Bromm V. (2002) *Mon. Not. Roy. Astron. Soc., 336*, 705-713.

Bate M. R., Bonnell I. A., and Bromm V. (2003) *Mon. Not. Roy. Astron. Soc., 339*, 577-599.

Beck T. L., Schaefer G. H., Simon M., Prato L., Stoesz J. A., and Howell R. R. (2004) *Astrophys. J., 614*, 235-251.

Berger E., Ball S., Becker K. M., Clarke M., Frail D. A., Fukuda T. A., Hoffman I. M., Mellon R., Momjian E., Murphy N. W., Teng S. H., Woodruff T., Zauderer B. A., and Zavala R. T. (2001) *Nature, 410*, 338-340.

Bonnell I. A., Bate M. R., Clarke C. J., and Pringle J. E. (1997) *Mon. Not. Roy. Astron. Soc., 285*, 201-208.

Bonnell I. A., Bate M. R., Clarke C. J., and Pringle J. E. (2001) *Mon. Not. Roy. Astron. Soc., 323*, 785-794.

Bonnell I. A., Bate M. R., and Vine S. G. (2003) *Mon. Not. Roy. Astron. Soc., 343*, 413-418.

Bouy H., Brandner W., Martín E. L., Delfosse X., Allard F., and Basri G. (2003) *Astron. J., 126*, 1526-1554.

Brandeker A., Jayawardhana R., and Najita J. (2003) *Astron. J., 126*, 2009-2014.

Chandler C. J., Brogan C. L., Shirley Y. L., and Loinard L. (2005) *Astrophys. J., 632*, 371-396.

Chauvin G., Ménard F., Fusco T., Lagrange A.-M., Beuzit J.-L., Mouillet D., and Augereau J.-C. (2002) *Astron. Astrophys., 394*, 949-956.

Chauvin G., Thomson M., Dumas C., Beuzit J.-L., Lowrance P., Fusco T., Lagrange A.-M., Zuckerman B., and Mouillet D. (2003) *Astron. Astrophys., 404*, 157-162.

Chick K. M. and Cassen P. (1997) in *Herbig-Haro flows and the birth of stars* (B. Reipurth and C. Bertout, eds.), p. 207, IAU Symp. 182, Kluwer, Dordrecht.

Ciardi D. R., Telesco C. M., Williams J. P., Fisher R. S., Packham C., Piña R., and Radomski J. (2003) *Astrophys. J., 585*, 392-397.

Ciardi D. R., Telesco C. M., Packham C., Gómez Martin C., Radomski J. T., De Buizer J. M., Phillips C. J., and Harker D. E. (2005) *Astrophys. J., 629*, 897-902.

Covey K. R., Greene T. P., Doppmann G. W., and Lada C. J. (2006) *Astron. J., 131*, 512-519.

Covino E., Catalano S., Frasca A., Marilli E., Fernández M., Alcalá J. M., Melo C., Paladino R., Sterzik M. F., and Stelzer B. (2000) *Astron. Astrophys., 361*, L49-L52.

Covino E., Frasca A., Alcalá J. M., Paladino R., and Sterzik M. F. (2004) *Astron. Astrophys., 427*, 637-649.

Curiel S., Girart J. M., Rodríguez L. F., and Cantó J. (2003) *Astrophys. J., 582*, L109-L113.

Dale J. E., Bonnell I. A., Clarke C. J., and Bate M. R. (2005) *Mon. Not. Roy. Astron. Soc., 358*, 291-304.

Delgado-Donate E. J., Clarke C. J., and Bate M. R. (2003) *Mon. Not. Roy. Astron. Soc., 342*, 926-938.

Delgado-Donate E. J., Clarke C. J., and Bate M. R. (2004a) *Mon. Not. Roy. Astron. Soc., 347*, 759-770.

Delgado-Donate E. J., Clarke C. J., Bate M. R., and Hodgkin S. T. (2004b), *Mon. Not. Roy. Astron. Soc., 351*, 617-629.

Duchêne G., Monin J.-L., Bouvier J., and Ménard F. (1999) *Astron. Astrophys., 351*, 954-962.

Duchêne G., Ghez A. M., McCabe C., and Weinberger A. J. (2003) *Astrophys. J., 592*, 288-298.

Duchêne G., Bouvier J., Bontemps S., André P., and Motte F. (2004) *Astron. Astrophys., 427*, 651-665.

Dulk G. A. (1985) *Ann. Rev. Astron. Astrophys., 23*, 169-224.

Duquennoy A. and Mayor M. (1991) *Astron. Astrophys., 248*, 485-524.

Durisen R. H., Sterzik M. F., and Pickett B. K. (2001) *Astron. Astrophys., 371*, 952-962.

Feigelson E. D. and Montmerle T. (1999) *Ann. Rev. Astron. Astrophys., 37*, 363-408.

Fischer D. A. and Marcy G. W. (1992) *Astrophys. J., 396*, 178-194.

Furlan E., Forrest W. J., Watson D. M., Uchida K. I., Brandl B. R., Keller L. D., and Herter T. L. (2003) *Astrophys. J., 596*, L87-L90.

Gammie C. F. (2001) *Astrophys. J., 553*, 174-183.

Ghez A. M., Neugebauer G., and Matthews K. (1993) *Astron. J., 106*, 2005-2023.

Ghez A. M., Weinberger A. J., Neugebauer G., Matthews K., and McCarthy D. W. Jr. (1995) *Astron. J., 110*, 753-765.

Girart J, M., Rodríguez L. F., and Curiel S. (2000) *Astrophys. J., 544*, L153-L156.

Girart J. M., Curiel S., Rodríguez L. F., Honda M., Cantó J., Okamoto Y. K., and Sako S. (2004) *Astron. J., 127*, 2969-2977.

Gómez L., Rodríguez L. F., Loinard L., Lizano S., Poveda A., and Allen C. (2006) *Astrophys. J.*, in press.

Goodwin S. P. and Kroupa P. (2005) *Astron. Astrophys., 439*, 565-569.

Goodwin S. P., Whitworth A. P., and Ward-Thompson D. (2004a) *Astron. Astrophys., 414*, 633-650.

Goodwin S. P. Whitworth A. P., and Ward-Thompson D. (2004b) *Astron. Astrophys., 423*, 169-182.

Greene T. P., Wilking B. A., André P., Young E. T., and Lada C. J. (1994) *Astrophys. J., 434*, 614-626.

Güdel M. (2002) *Ann. Rev. Astron. Astrophys., 40*, 217-261.

Guieu S., Dougados C., Monin J.-L., Magnier E., and Martín E. L. (2006) *Astron. Astrophys., 446*, 485-500.

Haisch Jr., K. E., Barsony M., Greene T. P., and Ressler M. E. (2002) *Astron. J., 124*, 2841-2852.

Haisch Jr., K. E., Greene T. P., Barsony M., and Stahler S. W. (2004) *Astron. J., 127*, 1747-1754.

Haisch Jr., K. E., Barsony M., Greene T. P., and Ressler M. (2006) *Astron. J.*, submitted.

Halbwachs J. L., Mayor M., Udry S., and Arenou F. (2003) *Astron. Astrophys., 397*, 159-175.

Hamaguchi K., Corcoran M. F., Petre R., White N. E., Stelzer B., Nedachi K., Kobayashi N., and Tokunaga A. T. (2005) *Astrophys. J., 623*, 291-301.

Hartigan P. and Kenyon S.J. (2003) *Astrophys. J., 583*, 334-357.

Hearty T., Fernández M., Alcalá J. M., Covino E., and Neuhäuser R. (2000) *Astron. Astrophys., 357*, 681-685.

Hillenbrand L. A. and White R. J. (2004) *Astrophys. J., 604*, 741-757.

Jensen E. L. N., Mathieu R. D., and Fuller G. A. (1994) *Astrophys. J., 429*, L29-L32.

Joergens V. (2006) *Astron. Astrophys., 446*, 1165-1176.

Johnston K. J., Fey A. L., Gaume R. A., Hummel C. A., Garrington S., Muxlow T., and Thomasson P. (2004) *Astrophys. J., 604*, L65-L69.

Johnston K. J., Fey A. L., Gaume R. A., Claussen M. J., and Hummel C. A. (2005) *Astron. J., 128*, 822-828.

Kiseleva L. G., Eggleton P. P., and Mikkola S. (1998) *Mon. Not. Roy. Astron. Soc., 300*, 292-302.

Konopacky Q. M., Ghez A. M., McCabe C., Duchêne G., and Macintosh B. A. (2006) *Astron. J.*, submitted.

Koresko C. D. (2000) *Astrophys. J., 531*, L147-L149.

Koresko C. D. (2002) *Astron. J., 124*, 1082-1088.

Kraus A. L., White R. J., and Hillenbrand L. A. (2005) *Astrophys. J., 633*, 452-459.

Kroupa P. (1995) *Mon. Not. Roy. Astron. Soc., 277*, 1491-1506.

Kroupa P., Petr M. G., and McCaughrean M. J. (1999) *New Astron., 4*, 495-520.

Lada C. J. (1987) in *Star Forming Regions*, (M. Peimbert and J. Jugaku, eds.), pp. 1-17, Reidel, Dordrecht.

Leinert Ch., Zinnecker H., Weitzel N., Christou J., Ridgway S. T., Jameson R., Hass M., and Lenzen R. (1993) *Astron. Astrophys., 278*, 129-149.

Lodato G. and Rice W. K. M. (2005) *Mon. Not. Roy. Astron. Soc., 358*, 1489-1500.

Loinard L. (2002) *Rev. Mex. Astron. Astrofis., 38*, 61-69.

Loinard L., Rodríguez L. F., D'Alessio P., Wilner D. J., and Ho P. T. P. (2002) *Astrophys. J., 581*, L109-L113.

Loinard L., Rodríguez L. F., and Rodríguez M. I. (2003) *Astrophys. J., 587*, L47-L50.

Loinard L., Mioduszewski A. J., Rodríguez L. F., González R. A., Rodríguez M. I., and Torres R. M. (2005) *Astrophys. J., 619*, L179-182.

Looney L. W., Mundy L. G., and Welch W. J. (2000) *Astrophys. J., 529*, 477-498.

Luhman K. L. (2001) *Astrophys. J., 560*, 287-306.

Mac Low M.-M. and Klessen R. S. (2004) *Rev. Modern Phys., 76*, 125-194.

Marchal L., Delfosse X., Forveille T., Ségransan D., Beuzit J.-L., Udry S., Perrier C., and Mayor M. (2003) in *Brown dwarfs* (Martín, ed.), p. 311, IAU Symp. 211, Astron. Soc. Pac., San Francisco.

Martín E. L., Barrado y Navascués D., Baraffe I., Bouy H., and Dahm S. (2003) *Astrophys. J., 594*, 525-532.

Mathieu R. D. (1994) *Ann. Rev. Astron. Astrophys., 32*, 465-530.

Mathieu R. D., Ghez A. M., Jensen E. L. N., and Simon M. (2000) in *Protostars and Planets IV* (V. Mannings, A. P. Boss and S. S. Russell, eds.), p. 703-730, Univ. of Arizona Press, Tucson.

Maxted P. F. L. and Jeffries R. D. (2005) *Mon. Not. Roy. Astron. Soc., 362*, L45-L49.

McCabe C., Ghez A. M., Prato L., Duchêne G., Fisher R. S., and Telesco C. (2006) *Astrophys. J., 636*, 932-951.

McDonald J. M. and Clarke C. J. (1995) *Mon. Not. Roy. Astron. Soc., 275*, 671-684.

Meeus G., Sterzik M., Bouwman J., and Natta A. (2003) *Astron. Astrophys., 409*, L25-L29.

Melo C. H. F. (2003) *Astron. Astrophys., 410*, 269-282.

Noriega-Crespo A., Moro-Martin A., Carey S., Morris P. W., Padgett D. L., Latter W. B., and Muzerolle J. (2004) *Astrophys. J. Suppl., 154*, 402-407.

Ochi Y., Sugimoto K., and Hanawa T. (2005) *Astrophys. J., 623*, 922-939.

Osterloh M. and Beckwith S. V. W. (1995) *Astrophys. J., 439*, 288-302.

Padoan P. and Nordlund A. (2002) *Astrophys. J., 576*, 870-879.

Patience J. and Duchêne G. (2001) in *The formation of binary stars* (H. Zinnecker and R. D. Mathieu, eds.), pp. 181-190, IAU Symp. 200, Astron. Soc. Pac., San Francisco.

Phillips R. B., Lonsdale C. J., Feigelson E. D., and Deeney B. D. (1996) *Astron. J., 111*, 918-929.

Prato L. and Simon M. (1997) *Astrophys. J., 474*, 455-463.

Prato L., Greene T.P., and Simon M. (2003) *Astrophys. J., 584*, 853-874.

Reipurth B. (2000) *Astron. J. 120*, 3177-3191.

Reipurth B. and Zinnecker H. (1993) *Astron. Astrophys., 278*, 81-108.

Reipurth B., Rodríguez L. F., Anglada G., and Bally J. (2002) *Astron. J., 124*, 1045-1053.

Reipurth B., Rodríguez L. F., Anglada G., and Bally J. (2004) *Astron. J., 127*, 1736-1746.

Ressler M. E. and Barsony M. (2001) *Astron. J., 121*, 1098-1110.

Rodríguez L. F. (1997) in *Herbig-Haro flows and the birth of stars* (B. Reipurth and C. Bertout, eds.), p. 83, IAU Symp. 182, Kluwer, Dordrecht.

Rodríguez L. F., D'Alessio P., Wilner D. J., Ho P. T. P., Torrelles J. M., Curiel S., Gómez Y., Lizano S., Pedlar A., Cantó J., and Raga A. C. (1998) *Nature, 395*, 355-357.

Rodríguez L. F., Porras A., Claussen M. J., Curiel S., Wilner D. J., and Ho P. T. P. (2003) *Astrophys. J., 586*, L137-L139.

Rodríguez L. F., Loinard L., D'Alessio P., Wilner D. J., and Ho P. T. P. (2005a) *Astrophys. J., 621*, L133-L136.

Rodríguez L. F., Poveda A., Lizano S., and Allen C. (2005b) *Astrophys. J., 627*, L65-L68.

Shu F. H., Adams F. C., and Lizano S. (1987) *Ann. Rev. Astron. Astrophys., 25*, 23-81.

Sigalotti L. Di G. and Klapp J. (2001) *Astron. Astrophys., 378*, 165-179.

Stassun K. G., Mathieu R. D., Vaz L. P. R., Stroud N., and Vrba F. J.. (2004) *Astrophys. J. Suppl., 151*, 357-385.

Steffen A. T., Mathieu R. D., Lattanzi M. G., Latham D. W., Mazeh T., Prato L., Simon M., Zinnecker H., and Loreggia D. (2001) *Astron. J., 122*, 997-1006.

Sterzik M. F. and Durisen R. H. (1995) *Astron. Astrophys., 304*, L9-L12.

Sterzik M. F. and Durisen R. H. (1998) *Astron. Astrophys., 339*, 95-112.

Sterzik M. F. and Durisen R. H. (2003) *Astron. Astrophys., 400*, 1031-1042.

Sterzik M. F. and Tokovinin A. A. (2002) *Astron. Astrophys., 384*, 1030-1037.

Sterzik M. F., Durisen R. H., and Zinnecker H. (2003) *Astron. Astrophys., 411*, 91-97.

Sterzik M. F., Melo C. H. F., Tokovinin A. A., and van der Bliek N. (2005) *Astron. Astrophys., 434*, 671-676.

Symington N. H., Harries T. J., Kurosawa R., and Naylor T. (2005) *Mon. Not. Roy. Astron. Soc., 358*, 977-984.

Tamazian V. S. (2004) *Astron. J., 127*, 2378-2381.

Tamazian V. S., Docobo J. A., White R. J., and Woitas J. (2002) *Astrophys. J., 578*, 925-934.

Tan J. C. (2004) *Astrophys. J., 607*, L47-L50.

Tohline J. E. (2002) *Ann. Rev. Astron. Astrophys., 40*, 349-385.

Tokovinin A. A. (2004) *Rev. Mex. Astron. Astrofis., 21*, 7-14.

Tokovinin A. A. and Smekhov M. G. (2002) *Astron. Astrophys., 382*, 118-123.

Tsujimoto M., Kobayashi N., and Tsuboi Y. (2005) *Astron. J., 130*, 2212-2219.

Valenti J. A. and Johns-Krull C. M. (2004) *Astrophys. and Space Science, 292*, 619-629.

Welty A.D. (1995) *Astron. J., 110*, 776-781.

Whitney B. A., Wood K., Bjorkman J. E., and Wolff M. J. (2003) *Astrophys. J., 591*, 1049-1063.

Woitas J., Köhler R., and Leinert Ch. (2001) *Astron. Astrophys., 369*, 249-262.

Wooten A. (1989) *Astrophys. J., 337*, 858-864.

Zuckerman B. and Song I. (2004) *Ann. Rev. Astron. Astrophys., 42*, 685-721.